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Three-Tier carbon accounting model for cities

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HIGHLIGHTS

- An EIO-LCA model for urban carbon footprint accounting is presented.
- The urban carbon emissions are calculated in three tiers in context of supply chain.
- Tier 3 carbon emissions cannot be ignored for efficient urban carbon mitigation policy.

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ABSTRACT

With the rapid population and economic growth, carbon emissions in cities have been increasing due to the accelerating urbanization, which provide great potential for global climate change mitigation. To measure the carbon emissions along the urban supply chain in terms of sectoral and urban horizons, this study tries to build a systematic carbon accounting framework to quantify sectoral indirect upstream supply chain emissions for effective urban carbon mitigation. An urban Three-Tier carbon accounting model has been established based on the Economic input-output life cycle assessment (EIO-LCA) method, concerning Tier 1: direct emissions; Tier 2: emissions from purchased secondary energy resource; and Tier 3: complete supply chain emissions. A case study of Chongqing city was conducted to identify the critical sectors of three tiers that contribute most to total carbon emissions, covering 28 economic sectors during 2002–2007. The results showed that emissions of Tier 1 and Tier 2 included in most protocols only occupy a small fraction (27.8%) of the total emissions of all 3 tiers, especially for industrial sectors. It is concluded that the existing climate-control protocols have underestimated the emissions of each sector and particularly, Tier 3 emissions have to be incorporated when formulating effective urban management strategies and climate adaptation planning. By incorporating the Three-Tier carbon footprint into sectoral input–output accounting framework, this study developed carbon sector specific categorizations to pursue emissions mitigation pathways not just within their own economic activity but also across their supply chain.

1. Introduction

As the home to over half of the global population and engines of growth for national economies, cities are the major contributors to the global carbon dioxide (CO_2) emissions [1], and have been recognized as leaders to implementing carbon emission mitigation strategies [2–3]. Incorporating carbon reduction goals into urban sustainable management has become a critical issue driven by the challenge to balance economic development and carbon emissions reduction over the past decade [4]. So far, 228 global cities with around 436 million people have set carbon emission reduction goals and targets.

Carbon footprint, defined from the life-cycle perspective, has been widely proven as a useful tool for carbon measurement [5]. An important issue related to carbon footprint is joint production, which arises commonly within supply chains. Each sector in urban economic system is not only producer that provides goods and services to other sectors but also consumer of products and services that produces carbon emissions (known as indirect emissions) [6]. The “producer” sector can influence the carbon emission of “consumer” sector through providing the intermediate goods and services, which is the impact of upstream supply chain on the sectoral carbon emission. Sectoral carbon emission from urban sectoral joint production within supply chains represents a significant proportion of total emissions [7]. For example, Huang et al. found that about 75 percent of an industry sector’s carbon footprint comes from upstream supply chain emissions [8]. While the assessments of supply chain emissions can help city to identify where the best opportunities lie for climate change mitigation, regardless of whether they occur within the urban boundary or within the supply chain from

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outside, little guidance is available for city to identify critical sectors and pathways to pursue emissions mitigation from entire supply chain perspective [9].

Urban carbon footprint in a supply chain differs in various system boundaries [10]. Here we defined it as the carbon emission embedded in both direct and indirect activities in specific urban economic sectors [11]. Meanwhile, there existed various carbon emission reduction protocols. The World Resources Institute and the World Council for Sustainable Development proposed the Greenhouse Gas Protocol in 2004, which has been widely accepted [12–13]. Besides, the Local Government Operation Protocol and the 2006 IPCC Guidelines for National Greenhouse Gas Inventories provided detailed and unified carbon emission accounting guidance incorporating different carbon sources and sinks into their accounting principle [14–15]. Even so, the routine reports from various institutions and existing researches on carbon emission accounting still largely ignored the supply chain carbon emissions in urban system [16–22], e.g., direct emissions and emissions from the generation of purchased electricity are often targeted with less focus on indirect emissions from sectoral upstream supply chain, and the impacts of sectoral linkage are largely neglected [6]. This results in large 'carbon leakage' because direct CO_2 emissions and emissions from purchased energy constitute only a small portion of the total carbon footprint [8]. Therefore, a precise estimation of the urban carbon footprint of the entire supply chain process is needed to pursue a low-carbon city.

To track the activities across a supply chain for a specific industry and assess the embodied CO_2 in a consumer product, life cycle assessment (LCA) has been widely introduced for carbon footprint calculation in practice [23]. LCA aggregates emissions across multiple subsystems (processes/sectors) to correctly estimate system-wide (supply chain-wide) emissions [24–28]. Currently, there are two major forms of LCA, i.e., the process-based LCA and economic input-output LCA (EIO-LCA). Process-based LCA models are more precise but difficult to obtain the detailed inventory data, and might lead to significant truncation errors due to an artificial cut-off when defining the system boundaries [29]. Economic input-output (EIO) models, proposed by Leontief in 1936 to aid in manufacturing planning [30], is introduced to improve the process-based LCA framework by reflecting the inter-relationships of various sectors via the production and consumption of intermediate economic outputs [31]. By aggregating the economic activities into sectors, the EIO model has been used in carbon footprint accounting framework to facilitate the impacts of urban sectoral economic activities and sectoral linkage on the carbon emission. There is a growing number of studies on the EIO-based carbon accounting for understanding the key drivers behind countries' growing resource use (energy consumption [32–34], energy and water [35–37], land and water use [38]) and carbon emissions [39–41]. The monetary transactions flowing among the economic sectors can be transformed to physical flows under the assumption that all outputs of a sector are produced with the same intensity of physical flow [42]. It is assumed that each industry consumes the outputs of various other industries in fixed ratios to produce its own unique and distinct output [43]. As traditional IO is constrained by aggregated sector representation, EIO-LCA has been developed to reduce the limitations of each individual approach and to increase their accuracies [44–45]. EIO-LCA methods can track all emissions across the supply chain for a specific sector and estimate all purchases and activities in a supply chain leading up to final manufacture in an industry [38]. In EIO-LCA, the environmental impact of carbon emissions is assumed to have a linear relationship with economic output in a specific sector with a steady state and conservation principle (i.e., the more products they produce, the more carbon they emit). These models have been recently applied in the accounting of carbon emissions at various scales, and related studies have been summarized in Table 1.

Considering the significant contribution of urbanization to carbon emissions, city could be used as an important handhold for carbon mitigation and adaptation practices [46–51]. There existed some

Table 1
Summary of carbon footprint related work.

Method	Scale	Results & conclusion	Study area	Authors
Inventory analysis	City level	18 typical cities that contain an average of 6.57% of the population and 7.91% of the GDP, contribute 13% of China's total CO_2 emissions.	Selected 18 cities from 6 central provinces	Xu et al. [1]
Input-output analysis	City level	Within the total carbon flow, import and export respectively accounted for 59 and 65%, highlighting the importance of emissions embodied in trade.	Xiamen	Lin et al. [18]
Top-down GHG inventories	City level	GHG emissions are mainly generated from energy use in industrial sector and coal-burning thermal power plants. Besides, the proportion of indirect GHG emission from imported energy use keeps growing, implying that big cities are further dependent on energy/material supplies from neighboring regions.	Chinese mega cites (Beijing, Tianjin, Shanghai and Chongqing)	Liu et al. [20]
Multi-scale integrated systems modelling	City level	Cross-sectoral strategies contribute an additional 15%–36% to national CO_2 mitigation, compared to conventional single-sector strategies.	637 cities of China	Ramaswami et al. [46]
EIO-LCA	National level	75 percent of an industry sector's carbon footprint comes from upstream supply chain emissions.	U.S.	Huang et al. [8]
Three-Tier model	National level	The CO_2 emissions from industrial processes are concentrated in the nonmetal mineral products sector, instruments, meters, cultural and office machinery sector, and the construction sector.	China	Yang and Chen [47]
EIO and structural decomposition analysis	National level	How changes in China's technology, economic structure, urbanization, and lifestyles affected CO_2 emissions of China are analyzed.	China	Peters et al. [48]
EIO-LCA	Various levels	Understanding the level of geographic resolution within large industrial nations needed to reach acceptable accuracy has not been well-tested across the broad spectrum of goods and services consumed.	U.S.	Yang et al. [49]
LCA	Various levels	Spatial differentiation in life cycle impact assessment: a decade of method development to increase the environmental realism of life cycle impact assessment.	Different cases	Potting et al. [50]
Input-output analysis	National	A consistent set of carbon inventories that spans the full supply chain of global CO_2 emissions, finding that 37% of global emissions are from fossil fuels traded internationally and 23% of global emissions are embodied in traded goods.	World	Davis et al. [51]

studies focusing on urban carbon emission accounting [52–55]. However, only a few of them considered the supply chain carbon emissions or explored the root causes of carbon emissions. Concerning the direct and indirect carbon emissions at city level, some studies have been carried out with the concept of three tiers category in context of supply chain. Matthews et al. firstly introduced the framework and assessed the levels of carbon footprint in 3 tiers: Tier 1 emissions are the direct emissions, Tier 2 refers to emissions from purchased secondary energy resource and Tier 3 emissions refer to the complete supply chain emissions, and further provided case studies in two sectors: book publishers and power generation [56]. Their results showed that direct emissions from an industry accounted for, on average, only 14% of the total supply chain CO_2 emissions (Tier 1 carbon emissions) while direct emissions plus emission from industry energy inputs (Tier 2 carbon emissions) occupied 26%. Larsen and Hertwich developed a carbon emissions inventory related to the municipal services in the city of Trondheim in Norway [11], showing that approximately 93% of the total carbon footprint of municipal services was due to indirect emissions covered by Tier 3. Huang et al. categorized Tier 3 carbon footprints of the US economic sectors by using an EIO-LCA model to identify upstream emission sources and suggested that protocol organizations should create more specific Tier 3 guidelines available by developing sector-specific categorization and implementing broader industry-specific protocols [7]. Chen et al. investigated supply chain carbon footprinting and responsibility allocation for supply chains involved in joint production from the perspective of a social planner to achieve social value optimization [9]. Similarly, Bi et al. deemed that benchmarks and more holistic carbon emission inventories based on the Three-Tier category at city level were very important for mitigating climate change, and analyzed the urban carbon emissions with six emission sources [54]. Employing the EIO-LCA, Lin et al. provided carbon footprint of Xiamen and analyzed the influence from cross-boundary economic activities [55].

While the Three-Tier model had been introduced and studied at national level, there is a lack of the studies for introducing this model to urban carbon accounting. Also, the internal characters of urban carbon emissions have not been well illustrated. Particularly, temporal changes of urban carbon emissions are often ignored, which may impede the understanding of driving forces hidden behind such emissions. The aim of this study was to establish an EIO-LCA model focusing on Three-Tier carbon emissions for urban sectors of agriculture, industry, transportation and tertiary industries. The upstream emission sources could be categorized and the sectors that significantly contributed to climate change in each tier could be identified. Taking Chinese low-carbon pilot megacity, Chongqing, as a case study, the proposed EIO-LCA method was applied to evaluate the upstream footprint of 28 economic sectors during 2002–2007 considering direct emissions, emissions from purchased energy and the total supply chain emissions. The rest of the paper is organized as follows. In the methodology section, the details of the Three-Tier model were presented. In Section 3, the proposed model was applied to account the carbon emissions of Chongqing city in context of different tiers. Finally, policy suggestions for the low carbon development of industries in Chongqing were outlined.

2. Method

2.1. Study area

Chongqing is one of the first national low-carbon pilot cities of China with over 30 million people. The city has 19 districts and 21 counties, which is the largest economic center in the upper reach of the Yangtze River and the hub of water and land transportation. Chongqing's energy consumption structure consists of primary industry (farming, forestry, animal husbandry and fishery), secondary industry (industry and construction), tertiary industry (other than transport), transportation, and household consumption. Chongqing's main terminal energy consumption is for production activities and household, among which production consumption is regarded as the main factor. The secondary industry is the major factor of production consumption. In 1997, the secondary industry energy consumption accounted for 86.0% of the total consumption, which slowly dropped to 62.34% in 2008 year by year. The energy consumption in the tertiary industry accounted for an increasing proportion of production energy, from 5.8% in 1997 to 16.9% in 2008, an annual increase of 1%. In the industrial sector, with the gradual upgrading of the industrial structure, the share of industry in GDP remains above 30%, and energy consumption is mainly for high-energy-consuming industries. In 2014, energy consumption in the electricity and heat production and supply, chemical raw materials and chemical products manufacturing, nonmetallic mineral products, smelting and pressing of ferrous metals, and coal mining and washing industries, etc. accounted for 79.16% of the total industrial energy consumption and 39.75% of total energy consumption [57]. Most of the energy consumption can be attributed to several large enterprises. For example, in 2007, the top 10 energy-consuming industrial enterprises in Chongqing consumed about 40% of the industrial energy in the whole city. Though 6.2 higher than the national average, energy consumption of the industrial added value in Chongqing was twice of those in Beijing and Shanghai, which were respectively 1.33 tce/10^4 RMB yuan and 1.20 tce/10^4 RMB yuan in the same period [19].

2.2. Basic concept

As shown in Fig. 1, Tier 1 includes direct emissions from a sector, covering emissions from natural gas and petroleum combustion, similar to the "producer perspective" used for emissions inventories of cities. Tier 2 includes emissions due to electricity and steam purchases for a sector. Tier 3 includes the total supply chain up to the production gate, also known as cradle-to-gate, emissions. The emission equations use some linear algebra that is common in the literature of EIO-LCA. The

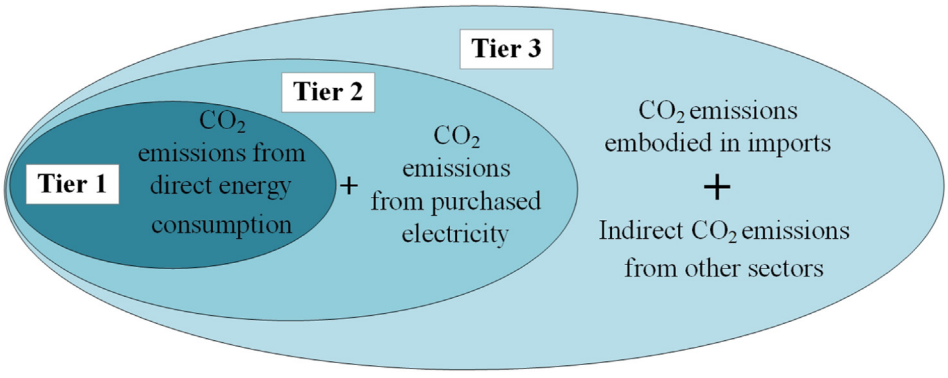


Fig. 1. Three-Tier carbon accounting framework for urban system.

Three-Tier model on carbon accounting of economic sectors for Chongqing city was developed as below:

Tier 1: includes direct emissions by energy consumption and industrial processes in each sector, i.e., from the combustion of coal, oil and natural gas, and also included the CO_2 emissions from industrial processes such as cement production. This is similar to the 'producer perspective' [22] used for emissions inventories of countries, states, cities, and so on.
Tier 2: covers the emissions due to purchased energy such as electricity and steam for a sector.
Tier 3: comprises the embodied CO_2 emissions from the consumption of primary energy based on production from the total supply chain up to the production gate and the CO_2 emissions from industrial processes, also known as cradle-to-gate emissions.

2.3. Three-Tier model

The Three-Tier model proposed by Matthews et al. [56] covered the direct emissions, the emissions from purchased energy and the supply chain emissions. Here we need to identify the significant carbon sources of each scope for a better carbon management. The accounting framework is consisting of energy related carbon emissions and industrial process emissions. As cement production is one of the largest carbon emission sources in Chongqing, the increasing urbanization rate and expanding construction areas demand for large amounts of cement production, which rapidly enhances the carbon emission of cement production industries. Since cement production is the largest non-energy CO_2 emission sources, the non-energy CO_2 emissions from this sector are specified to represent emissions from industrial processes in this paper. The accounting models used for estimating all purchases and activities in a supply chain lead to final manufactures in an industry by any sector in Chongqing based on the EIO-LCA [58–61].

2.3.1. Tier 1 model

Tier 1 model accounts the direct production emissions of a specific sector, as given below:

$$\mathbf{E_1} = [E_{1,1} \;\; E_{1,2} \;\; \cdots \;\; E_{1,28}] = \mathbf{F_e} * \mathbf{E^d} + \mathbf{F} * \mathbf{P}$$

$$= [F_{e1} \;\; F_{e2} \;\; F_{e3}] * \begin{bmatrix} E^d_{1,1} & E^d_{1,2} & \cdots & E^d_{1,28} \\ E^d_{2,1} & E^d_{2,2} & \cdots & E^d_{2,28} \\ E^d_{3,1} & E^d_{3,2} & \cdots & E^d_{3,28} \end{bmatrix} + [F_1 \;\; F_2 \;\; \cdots \;\; F_{28}] * \begin{bmatrix} P_1 & 0 & \cdots & 0 \\ 0 & P_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & P_{28} \end{bmatrix} \quad (1)$$

where $\mathbf{E_1}$ is the 1×28 matrix (specifying CO_2 emissions from the 28 economic sectors); $\mathbf{E^d}$ is the 3×28 matrix specifying use of three energy types in 28 sectors, including coal, oil and natural gas; $\mathbf{F_e}$ is the 1×3 matrix of CO_2 emission coefficients of three energies; $\mathbf{F}$ is the 1×28 matrix representing the CO_2 emissions from industrial processes per unit Gross Domestic Product (GDP) of 28 production sectors. For most of industrial sectors, the carbon emission are mainly from their energy consuming activities. However, for the cement production, most of them are from raw materials calcined decomposition and cement kiln fuel combustion, while the emissions from energy consumption only occupy about 40%. Thus, in this study, industrial process emissions from cement production are accounted. Here $\mathbf{P}$ is the 28×28 vector that represents the output values of 28 sectors.

2.3.2. Tier 2 model

The Tier 2 model concerns the carbon emissions embodied in the purchased energy resources. Although these emissions are not generated onsite, they should be taken into accounting as the electricity is consumed from a consumer perspective. The Tier 2 model can be presented as:

$$\mathbf{E}_2 = [E_{2,1} \;\; E_{2,2} \;\; \cdots \;\; E_{2,28}] = \mathbf{F_e} * \mathbf{E^p} + \mathbf{F} * \mathbf{P}$$

$$= [F_{e1} \;\; F_{e2} \;\; F_{e3}] * \begin{bmatrix} E^p_{1,1} & E^p_{1,2} & \cdots & E^p_{1,28} \\ E^p_{2,1} & E^p_{2,2} & \cdots & E^p_{2,28} \\ E^p_{3,1} & E^p_{3,2} & \cdots & E^p_{3,28} \end{bmatrix} + [F_1 \;\; F_2 \;\; \cdots \;\; F_{28}] * \begin{bmatrix} P_1 & 0 & \cdots & 0 \\ 0 & P_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \vdots & P_{28} \end{bmatrix} \quad (2)$$

where $\mathbf{E}_2$ is the 1×28 matrix; $\mathbf{E^p}$ is the specifying use of purchased energies, such as electricity; $\mathbf{F_e}$ is the CO_2 emission coefficients of purchased energies. In addition, Munksgaard and Pedersen proposed the "actual energy consumption" principle [52]. By this principle, all emissions caused by electricity production are specified for each of the fuel inputs (e.g., coal, natural gas and fuel oil), which are used for power generation, while zero emissions are connected to the final use of the electricity and district heating. The CO_2 emissions from purchased electricity are then allocated to different sectors based on the electricity consumption structure.

2.3.3. Tier 3 model

The calculation of the Tier 3 model is based on the IO table, which shows monetary interactions or exchanges between the economic sectors and therefore their interdependence. The rows of an IO table describe the distribution of a sector's output throughout the economy while the columns describe the inputs required by a particular sector to produce its output [56]. The basic IO model derives the total economic purchases (i.e., supply chain) across an economy required to make a vector of desired output, commonly called the "final demand" [62], as shown as:

$$X = (I + A + A \times A + A \times A + A \times \cdots)Y = (I - A)^{-1}Y \quad (3)$$

By multiplying the required inputs X with the energy consumption vector E^d and the CO_2 emission coefficient matrix F_i, the direct and indirect emissions generated from energy consumption in the supply chain can be calculated as:

$$\mathbf{E_e} = \mathbf{F} * \mathbf{E^d} (\mathbf{I} - \mathbf{A})^{-1} \mathbf{Y} \quad (4)$$

where $\mathbf{E_e} = [E_{e,1} \;\; E_{e,2} \;\; \cdots \;\; E_{e,28}]$ is a 1×28 matrix, signifying the supply chain CO_2 emissions from energy consumption in 28 production sectors. $\mathbf{A} = \begin{bmatrix} A_{1,1} & A_{1,2} & \cdots & A_{1,28} \\ A_{2,1} & A_{2,2} & \cdots & A_{28} \\ \vdots & \vdots & \ddots & \vdots \\ A_{28,1} & A_{28,2} & \cdots & A_{28,28} \end{bmatrix}$ is a matrix of intermediate consumption where the columns represent the input from each industry to produce one unit of output for each industry. $(\mathbf{I}-\mathbf{A})^{-1}$ is the 28×28 Leontief inverse coefficient matrix. $\mathbf{Y} = \begin{bmatrix} Y_1 & 0 & \cdots & 0 \\ 0 & Y_2 & \cdots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \cdots & Y_{28} \end{bmatrix}$ is the 28×28 vector, which represents the final demands of 28 sectors. Considering the non-energy industrial process emissions, the total emissions E_3 in a consumer perspective are calculated by:

$$\mathbf{E_3} = \mathbf{F}*\mathbf{E^d}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{Y} + \mathbf{E}(\mathbf{I}-\mathbf{A})^{-1}\mathbf{Y} \quad (5)$$

where $\mathbf{E_3}$ is the sum of CO_2 emissions from both energy consumption and industrial process. $\mathbf{E}$ is the 1×28 matrix specifying the CO_2 emissions from industrial processes per unit GDP for 28 production sectors. In this paper, only the non-energy industrial process CO_2 emissions of the Nonmetal Mineral Products sector (cement production) are considered due to data availability.

The carbon content in the exported products (C_E) can be calculated by multiplying the Tier 3 (E_3) carbon emission matrix by the export matrix (M_E) divided by domestic carbon matrix (M_T) excluding the import; hence the export of the carbon can be calculated by:

$$C_E = E_3 \times \frac{M_E}{M_T} \quad (6)$$

As for the calculation of carbon import (C_I), when a region imports a commodity, it transfers the carbon from certain regional intermediate input products during the manufacturing process. Similarly, combing the import matrix (M_I) and domestic carbon matrix (M_T), the import of the carbon can be calculated by:

$$C_I = E_3 \times \frac{M_I}{M_T} \quad (7)$$

Thus, the net exports (C_N) of Tier 3 carbon of a region can be expressed as:

$$C_N = C_E - C_I \quad (8)$$

2.4. Data sources

The EIO-LCA was developed for assessing environmental impacts of sectors in Chongqing city taken from the 2007 Input-Output Table in China [63]. Due to the lack of similar tables for the years 2003–2007, we assumed that the Leontief inverse coefficient $(I\text{-}A)^{-1}$ for these years was identical to the baseline year 2007. Energy data for the years 1997–2014 were obtained from the Chongqing Statistical Year book 1998–2015 [57]. The final consumption of energy is specified for 4 types of sources: coal, oil, natural gas and electricity.

CO_2 emission factors of primary energy were calculated based on the carbon content of the fuels and the type of energy, which were included in 2006 IPCC Guidelines for National Greenhouse Gas Inventories [15]. CO_2 emission factor of electricity was based on coal and corrected according to standard coal consumption for power supply (i.e., 366 g/kWh, which is the average value of China [64]) and the efficiency of the thermal power plant (71.5% is the average value of Chongqing). CO_2 emission factors for renewable energy were considered to be zero. The CO_2 emission factors are shown in Table 2 [47].

Considering that there are no CO_2 emissions from the consumption of electricity and heating, the principle of its calculation is that electricity and heating is regarded as the final consumption, which means it is estimated as the carbon emissions from its material and energy inputs. While there is no district heating in Chongqing region, in this study, only the CO_2 emissions from the electricity consumption are estimated as the carbon emissions from its material and energy inputs based on above mentioned principle.

The economic IO tables encompass 42 sectors, and the energy-flow table contains energy consumption information for 40 sectors. However, to retain consistency between the two datasets, new classification principles were used for the years 2002–2014 and the sectors categorized into the 28 types were shown in Table 3.

Table 2
The carbon emission coefficients of various energy sources.

NO.	1	2	3	4
Energy type	Coal ($kgCO_2$/GJ)	Oil ($kgCO_2$/GJ)	Natural gas ($kgCO_2$/GJ)	Electricity ($kgCO_2$/kWh)
Carbon emission coefficients	90.90	72.93	51.19	0.6963

3. Results

3.1. Comparison of Tier 1, Tier 2 and Tier 3 CO_2 emissions

Fig. 2 shows the structure and amount of CO_2 emissions from 3 types of energy sources at the sectoral level in 2007. Electricity, Steam Production and Supply sector had the largest CO_2 emissions (3.80E + 07 t), while Smelting and Pressing of Metals, Coal Mining and Dressing, as well as Transportation, Storage, Postal and Telecommunication Services had nearly 1.00E + 07 t CO_2. Farming, Forestry, Animal Husbandry and Fishery, Transportation, Storage, Postal and Telecommunication Services sector including also contributed significantly to the CO_2 emissions. Meanwhile, coal was generally the largest contributors to sectoral CO_2 emissions, representing about 50–99%. This highlighted the dominant role of coal in most industries and urban electricity supplies. In addition, oil use had an average of 95% CO_2 in Water Production and Supply, Transportation, Storage, Postal and Telecommunication Services, as a consequence of widely used fuel vehicles in these two sectors.

The calculations show that Tier 1 and Tier 2 as defined by current urban carbon footprint protocols include only a small fraction of the total supply chain (Tier 3) for most sectors. As Fig. 3 shows, only 27.8% of Tier 3 are captured by Tier 1 and Tier 2. For Tier 1, the top three CO_2 emission sectors in 2007 just cover 83.28% (Sector 2), 72.76% (Sector 22) and 71.34% (Sector 5) of Tier 3 while the three lowest sectors cover 2.62% (Sector 19), 1.66% (Sector 23) and 1.55% (Sector 24). For Tier 2, the top three sectors cover 86.76% (Sector 2), 85.05% (sector 24) and 82.87% (Sector 22) and the three lowest cover 4% (Sector 18), 4.73% (sector 8) and 4.88% (Sector 23).

These 28 sectors, comprising 70% of all economic sectors, have less than 40% of their total CO_2 emissions represented by Tier 1 and Tier 2 emissions. This indicates that a large quantity of CO_2 emissions may be underestimated according to the narrowly defined estimation protocols. Three sectors that have most of their footprint (> %) represented by direct emissions in Tier 1 and Tier 2 include coal mining and dressing, nonmetal minerals mining and dressing, and electricity and steam production and supply (i.e., sectors 2, 5 and 22, respectively). Therefore, their total Tier 3 footprint can be accurately estimated with the Tier 1 boundary alone. For the water production and supply sector (sector 24), Tier 1 captures 1.55% of the total CO_2 emissions, and Tier 2, 80.05%, which demonstrates that the emissions from this sector are mainly based on purchased energy; the carbon footprint is therefore generated by the emissions from electricity production.

3.2. Comparison of industrial process and energy consumption emissions

Carbon emissions not only come directly from energy consumption, but also indirectly from material consumption, which emits CO_2 in the industrial process, such as cement, steel, and lime. Due to the carbon emission contribution of production process for cement production is large and the lack of data for other processes, only the contribution of cement production was calculated in this paper. Fig. 4 shows the Tier 3 CO_2 emissions from industrial processes and energy consumption in 2007, with the same unit for carbon emissions. It can be seen that the indirect carbon emissions from cement production contribute considerably to the total emissions from sectors 5, 12, 13, 14, and 25.

Importantly, CO_2 emissions from industrial processes in sector 5, the nonmetal mineral mining and dressing sector, occupy 38.88% of Tier 3, and as Fig. 5 shows, cannot be neglected; this is followed by sectors 12, 13 and 25 (at 4.58%, 5.97% and 5.98%, respectively). If data were available for the other sectors, the CO_2 emissions from industrial processes would be larger.

Table 3
Sector classification of Chongqing city.

Sector code	Aggregated 28 sectors	Original 45 sectors	Original sector number
1	Farming, Forestry, Animal Husbandry and Fishery	Farming, Forestry, Animal Husbandry, Fishery and Water Conservancy	1
2	Coal Mining and Dressing	Coal Mining and Dressing	2
3	Petroleum and Natural Gas Extraction	Petroleum and Natural Gas Extraction	3
4	Metals Minerals Mining and Dressing	Ferrous Metals Mining and Dressing	4
		Nonferrous Metals Mining and Dressing	5
5	Nonmetal Minerals Mining and Dressing	Nonmetal Minerals Mining and Dressing	6
		Other Minerals Mining and Dressing	7
6	Food Production and Tobacco Processing	Food Processing	8
		Food Production	9
		Beverage Production	10
		Tobacco Processing	11
7	Textile Industry	Textile Industry	12
8	Garment, Leather Furs Down and Related Products	Garments and Other Fiber Products	13
		Leather, Furs, Down and Related Products	14
9	Timber Processing and Furniture Manufacturing	Timber Processing, Bamboo, Cane, Palm Fiber & Straw Products	15
		Furniture Manufacturing	16
10	Paper making, Printing and Cultural Educational and Sports Goods	Papermaking and Paper Products	17
		Printing and Record Medium Reproduction	18
		Cultural, Educational and Sports Articles	19
11	Petroleum, Coking and Nuclear Fuel Processing	Petroleum Processing and Coking	20
12	Chemical Industry	Raw Chemical Materials and Chemical Products	21
		Medical and Pharmaceutical Products	22
		Chemical Fiber	23
		Rubber Products	24
		Plastic Products	25
13	Nonmetal Mineral Products	Nonmetal Mineral Products	26
14	Smelting and Pressing of Metals	Smelting and Pressing of Ferrous Metals	27
		Smelting and Pressing of Nonferrous Metals	28
15	Metal Products	Metal Products	29
16	Ordinary and Special Equipment	Ordinary Machinery	30
		Equipment for Special Purposes	31
17	Transportation Equipment	Transportation Equipment	32
18	Electric Equipment and Machinery	Electric Equipment and Machinery	33
19	Communication Equipment, Computers and Other Electronic Equipment	Electronic and Telecommunications Equipment	34
20	Instruments, Meters, Cultural and Office Machinery	Instruments, Meters, Cultural and Office Machinery	35
21	Other Manufacturing Industry	Other Manufacturing Industry	36
22	Electricity, Steam Production and Supply	Production and Supply of Electric Power, Steam and Hot Water	37
23	Gas Production and Supply	Production and Supply of Gas	38
24	Water Production and Supply	Production and Supply of Tap Water	39
25	Construction	Construction	40
26	Transportation, Storage, Postal and Telecommunication Services	Transportation, Storage, Post and Telecommunication Services	41
27	Wholesale, Retail Sale Trade and Catering Trade	Wholesale, Retail Trade and Catering Services	42
28	Others	Logging and Transport of Wood and Bamboo	43
		Scrap and waste	44
		Others	45

3.3. Tier 3 CO_2 emissions

For Tier 3, which represents the total CO_2 emissions, the top three sectors were transportation equipment (sector 17), smelting and pressing of metals (sector 14), and electricity, steam production and supply (sector 22) in 2007 (Fig. 6).

Transportation equipment, one of the primary industries in Chongqing, is a sector with low Tier 1 and Tier 2 emissions relative to the total urban carbon footprint. This is because supply chain processes such as the manufacturing of steel, metals and non-metals fall outside the traditional Tier 1 and Tier 2 footprint and are well-known for the high consumption of fossil fuels. Smelting and pressing of metals is another sector with large underestimations in Tier 1 and Tier 2 because the embodied CO_2 emissions in the raw mineral inputs are relatively high. In contrast, the electricity, steam production and supply sector also has high direct emissions from the burning of fossil fuels such as coal and 72.76% of its total emissions maps to Tier 1.

We then examined the Tier 3 emissions of sectors 14, 22 and 17 from 2002 to 2007 (see Fig. 7). The CO_2 emissions of the smelting and pressing of metals, i.e., sector 14, changed dramatically from 1.64E+07 t in 2002 to 4.14E+07 t in 2007. The main reason for that lies in the production increasing for smelting and pressing of metals sector, that its sectoral economic output had increased over three times from the 16.92E+09 in 2002 to 57.17E+09 Yuan in 2007. With the same upward trend, CO_2 emissions from sector 17, the sector of transportation equipment, increased from 2.72E+07 t in 2002 to 5.48E+07 t in 2007. Finally, from 2002 to 2007, the CO_2 emissions of the total supply chain of sector 22, the electricity, steam production and supply sector, showed an increase to 3.69E+07 t in 2007, primarily due to the increasing demand for electricity power in Chongqing.

3.4. CO_2 emission intensity

CO_2 emission intensity here is defined as the ratio of CO_2 released to Gross Domestic Production (GDP), which can be used to determine the trade-off between low-carbon optimization and economic development. The lower the CO_2 emission intensity, the better the extent of low-carbon optimization embedded in economic advancement. As shown in Fig. 8, the highest CO_2 emission intensity in 2007 was observed for the coal mining and dressing sector (sector 2), followed by the nonmetal minerals mining and dressing (sector 5) and petroleum, coking and nuclear fuel processing (sector 11) sectors.

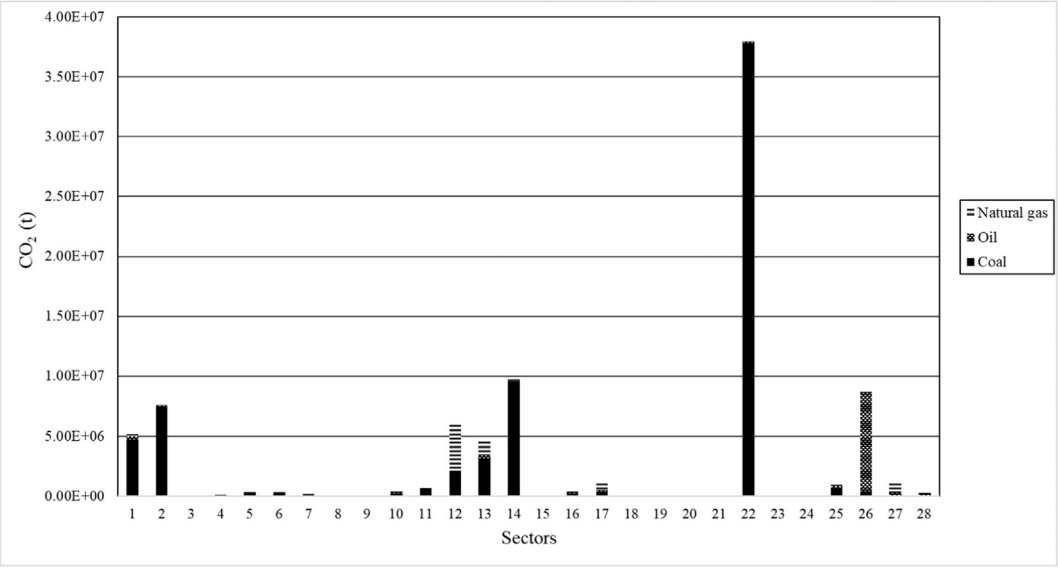


Fig. 2. CO_2 emissions from 3 energy types of 28 sectors in 2007.

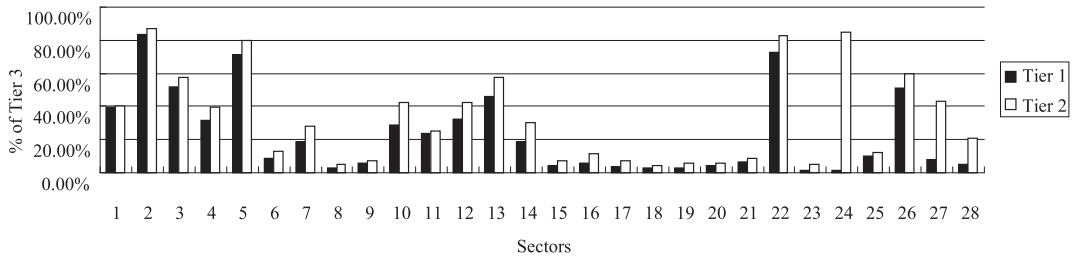


Fig. 3. The ratios of sector-specific CO_2 emissions form Tier 1 and Tier 2 to Tier 3 in 2007.

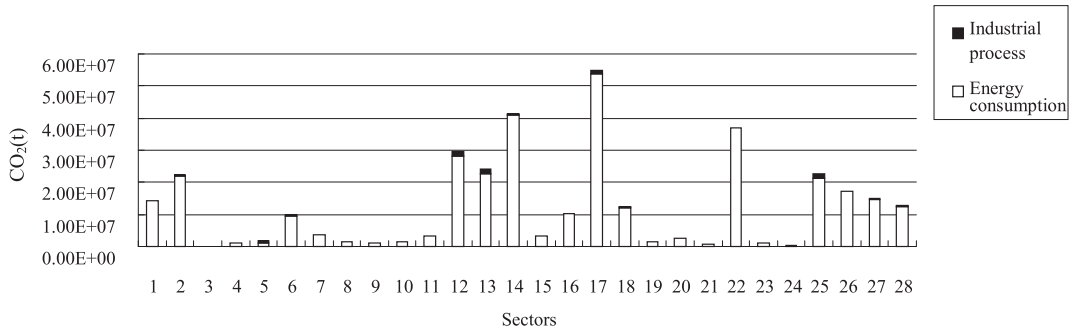


Fig. 4. Tier 3 CO_2 emissions from industrial processes and energy consumption in 2007.

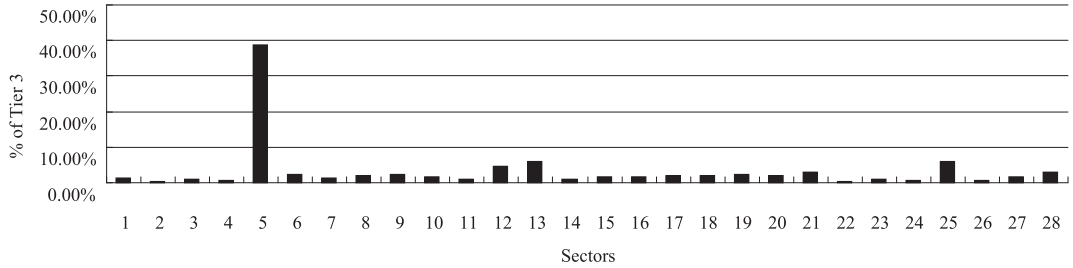


Fig. 5. The ratios of CO_2 emissions from industrial processes to total Tier 3 carbon emissions in 2007.

If compared with Fig. 6, these three sectors are low CO_2 emitters with most of their emissions made up of direct emissions from the burning of fossil fuels. Next, we compared the time-dependent variations of CO_2 emission intensity for sectors 2, 5 and 11 from 2002 to 2007 (Fig. 9). If the CO_2 emissions of a sector grow faster than the GDP, the emission intensity increases over time, indicating that the sector is unable to limit its CO_2 emissions in spite of GDP growth. With the energy structure optimization and proportion of clean energy

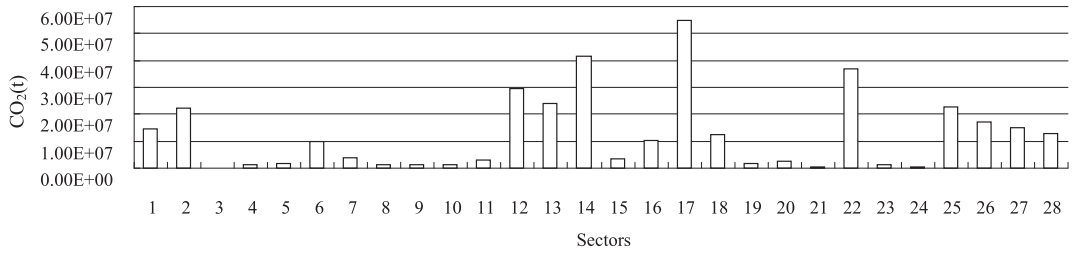


Fig. 6. Sector-specific CO_2 emissions in Tier 3 in 2007.

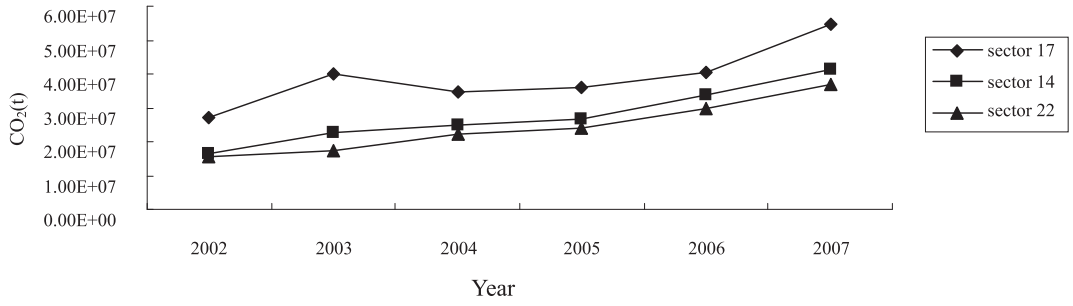


Fig. 7. Annual CO_2 emissions in Tier 3 from sectors 14, 17 and 22 during 2002–2007.

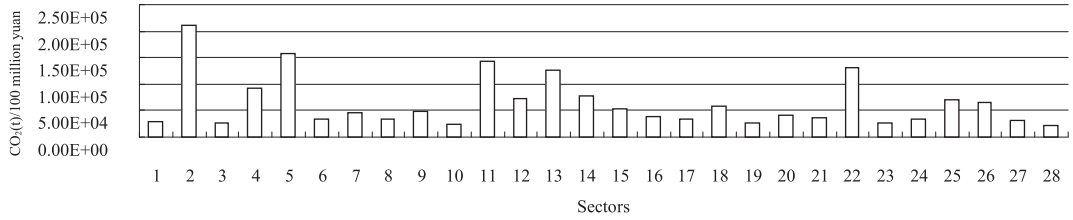


Fig. 8. Sector-specific CO_2 emission intensities in Tier 3 in 2007.

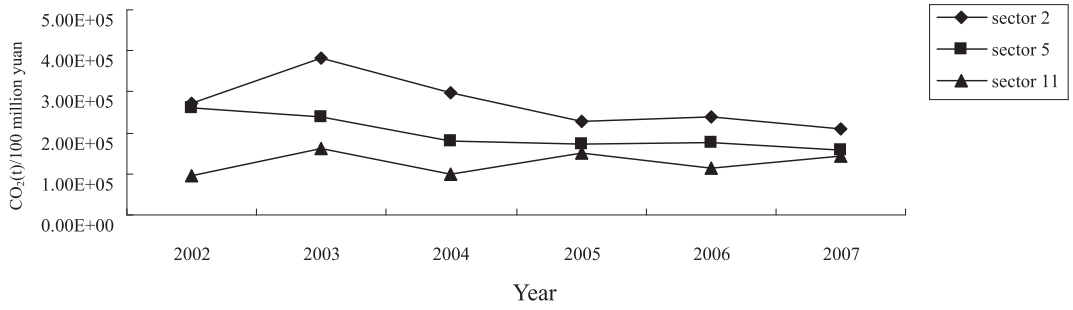


Fig. 9. CO_2 emission intensity in Tier 3 from sectors 2, 5 and 11 during 2002–2007.

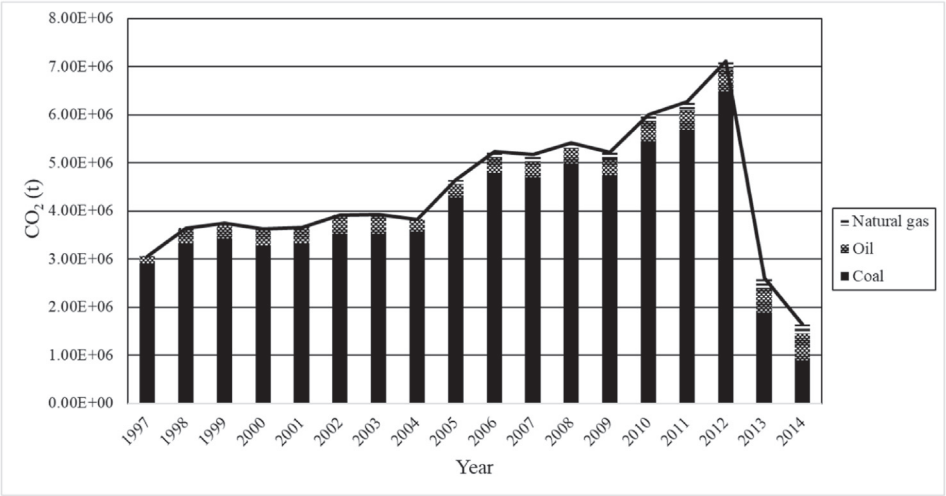
improvement, the percentage of coal for the total primary energy had been adjusted below 50% in Chongqing. Thus, in Chongqing city, CO_2 emission intensity either decreased or kept stable from 2002 to 2007 for all three sectors. The CO_2 emission intensity of the coal mining and dressing sector and the nonmetal minerals mining and dressing sector decreased from 2.72E+5 and 2.60E+5 t CO_2/100 million Yuan in 2002, respectively, to 2.10E+5 and 1.57E+5 t CO_2/100 million Yuan in 2007, respectively. For the petroleum, coking and nuclear fuel processing sector, the value of CO_2 emission intensity fluctuated from year to year with an overall slight but insignificant increase.

3.5. CO_2 emission for top 5 sectors

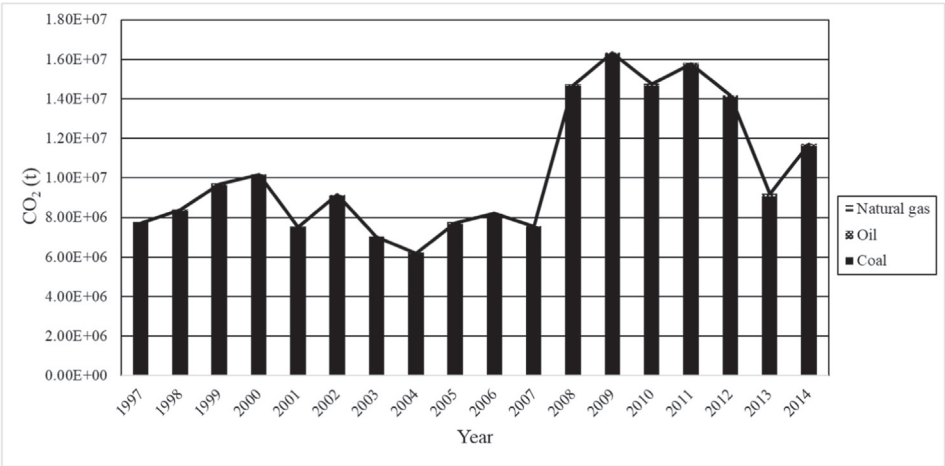
The CO_2 emissions from different energy types in Tier 3 for top 5 sectors during 1997–2014 were analyzed individually as shown in Fig. 10. The CO_2 emissions for Farming, Forestry, Animal Husbandry and Fishery sector were shown in Fig. 10(a). Overall, the CO_2 emissions of Farming, Forestry, Animal Husbandry and Fishery sector increased from 0.31E+07 t in 1997 to 7.10E+07 t in 2012 and finally decreased to 1.60E+07 t in 2014, which was over doubled during the first 15 years. In terms of the individual types of energy, the share of coal-related CO_2 emissions remained above 90% until 2012 and oil together with gas stayed below 10% over the past decades. In particular, the proportion of the CO_2 emissions from oil and gas increased from 5% in 1997 to 45% in 2014, which reflected that energy structure transformation in the agriculture sector has made significantly progress.

As shown in Fig. 10(b), the total CO_2 emission from Coal Mining and Dressing sector presents an increasing trend over the period of 1997–2014 (7.70–11.70E+07 t CO_2). However, the composition of the CO_2 emissions didn't changed significantly during the research period. The CO_2 emissions of coal accounted for nearly 99% of the total emission while oil and gas CO_2 emissions add up to no more 1%.

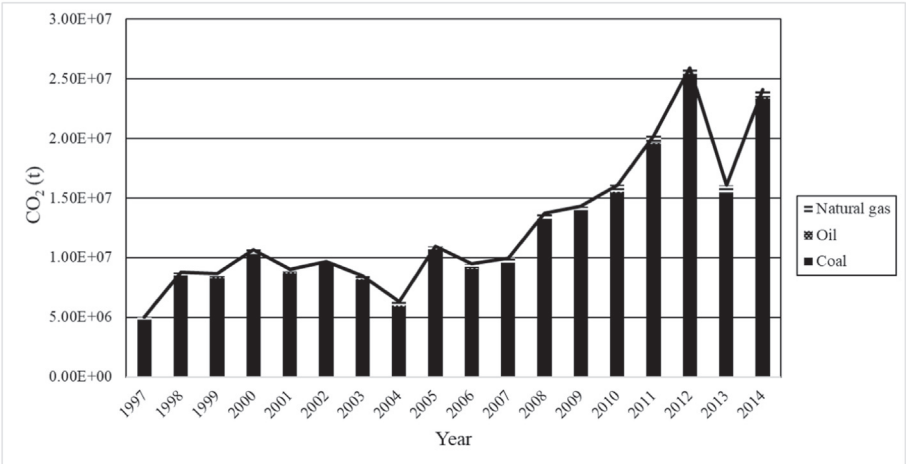
As shown in Fig. 10(c), the CO_2 emission in Smelting and Pressing of Metals sector increased rapidly from 1997 (5.10E+07 t CO_2) to 2014



(a) Farming, forestry, animal husbandry and fishery



(b) Coal mining and dressing

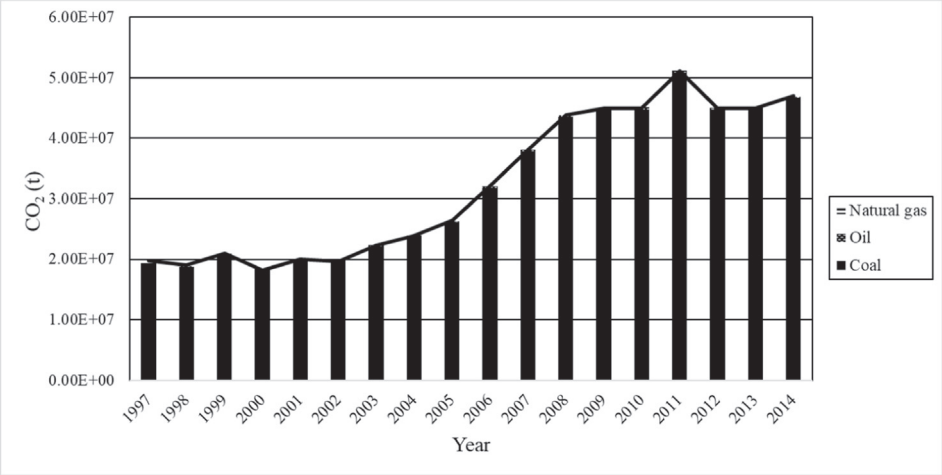


(c) Smelting and pressing of metals

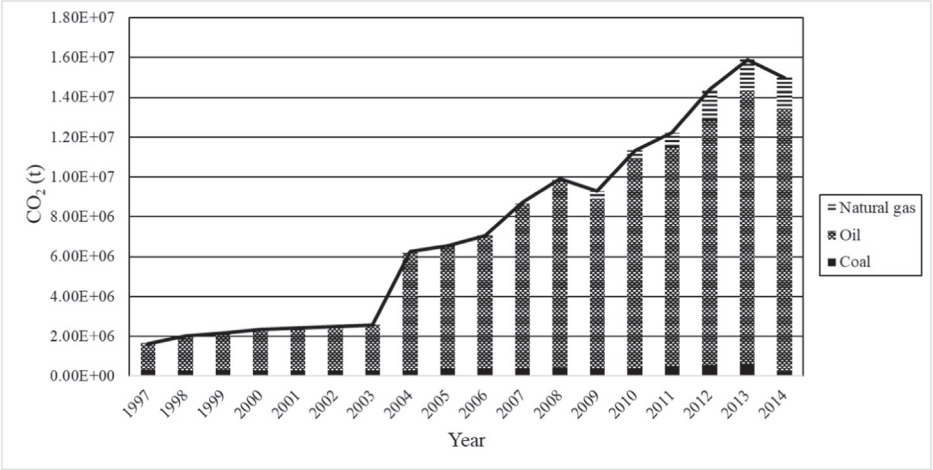
Fig. 10. CO_2 emissions in Tier 3 from different energy types for top 5 sectors during 1997–2014.

(24.00E + 07 t CO_2) with an average annual growth rate of 9.7%. As for the individual types of energy, the share of coal-related CO_2 emissions remained about 96% and oil together with gas stayed below 5% over the past decades.

As shown in Fig. 10(d), in general, the CO_2 emission of Electricity, Steam Production and Supply sector increased from 19.70E + 07 t in 1997 to 47.02E + 07 t in 2014, which had over doubled during the research period. Similarly, the composition of the CO_2 emissions had not changed significantly during the decades, the CO_2 emissions of coal accounted for nearly 99% of the total emission while oil and gas CO_2



(d) Electricity, steam production and supply



(e) Transportation, storage, postal and telecommunication services

Fig. 10. (*continued*)

emissions added up to no more 1%. However, this value decreased to 31% in 2000.

As shown in Fig. 10(e), the CO_2 emission increase in the Transportation, Storage, Postal and Telecommunication Services sector is consistent with the fact that Chinese travel models had shifted toward a private-vehicle leading structure. Specifically, the share of oil-related CO_2 emission remained about 80% even over 95% before 2010, and this ratio decreased since 2010 as a result of new-energy vehicle generalization.

3.6. CO_2 emissions exports and imports

The embodied CO_2 emissions imports and exports from Chongqing are shown in Fig. 11. Over all, Chongqing was a net importer, imported emissions were larger than exports, with a net imported value of 13.20E + 07 t CO_2. Urban carbon flows therefore came from surrounding regions like Sichuan, then flowing out to the other regions such as Anhui, Shanxi, Fujian and Jiangxi. Owing to the large amount of traded products and services, the emissions embodied in import were as much as 14.10E + 07 t CO_2, indicating the importance of embodied carbon emissions in trade, especially for rapidly developing cities. The CO_2 emissions import from developed regions (Guangdong and Shanghai) represented 28% (totaling 4.00E + 07 t CO_2), which was much more than those of the developing regions in Northwest (generally less than 5%). Anhui was the largest exporting target among thirty regions, representing about 49% (with a total amount of 4.50E + 07 t CO_2) of all the exported emissions from Chongqing. And Shanxi, Fujian took 26% and 13% proportions of CO_2 emissions export from Chongqing, respectively.

4. Conclusions

This paper established an EIO-LCA model for cities and used Chongqing as a case to analyze the energy supply and carbon emission chains of 28 economic sectors. We find that the first 2 tiers of emissions, included in most protocols, only cover a small fraction-on average, 27.8%-of the total supply chain, especially for industrial sectors. Therefore, for a complex process, different sectors in the supply chain will be responsible for the emissions, such as the supply of raw materials and individual steps in the industrial process. In accordance with the results of Huang et al., the upstream supply chain emissions (Tier 3 carbon emission) are responsible for 70–80% of total carbon emission for most manufacturing industries in the US case, our Chongqing case with the percentage of 72.2%. Similar to the results of Yang and Chen, our calculation also indicate that the existing climate-control protocols have underestimated the emissions of each sector, and Tier 3 emissions have to be considered to design effective management strategies and climate change policies. Thus, a broader definition of urban carbon footprint is required to promote effective corporate carbon mitigation policies. However, without quantitative indicators of the total supply chain of each sector, these decisions cannot be made. A system for public reporting of CO_2 intensity has to be established and for sectors of

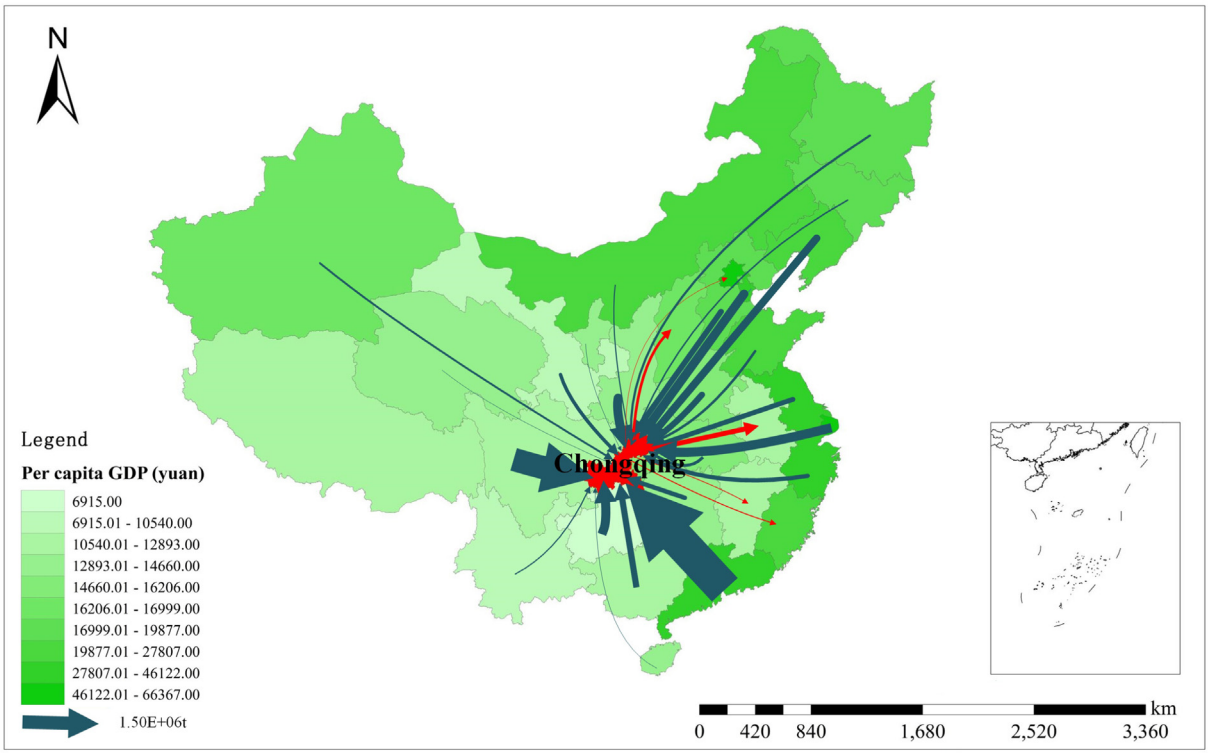


Fig. 11. Imports and exports of CO_2 emissions from Chongqing in 2007.

high CO_2 emission intensity, energy pricing and fiscal policies, tight oversight of industrial energy, closure of inefficient facilities and other emission control financial policies have to be implemented. Thus, our sectoral Three Tier carbon emissions results demonstrating the sectoral differences among the direct and supply chain carbon emission can be a compensate for urban carbon emission control financial policies design.

5. Discussion

As with any calculation based on EIO-LCA methods, this method has uncertainties inherent in EIO-LCA, which is related to sectoral aggregation; price, temporal and spatial variation. Especially, when implementing EIO-LCA for carbon emissions accounting, the special assumption is that carbon emissions are assumed to have a linear relationship with economic output in a specific sector with a steady state and conservation principle. (i.e., the more products they produce, the more carbon they emit). Along with the special assumption, the sector aggregation introduces additional uncertainties for the carbon emissions accounting. The variability in different companies' actual environmental intensity in the same sector is not considered. For example, the carbon intensity of electricity production can vary significantly depending on the respective energy generation portfolio for the electricity grid. Thus, aggregation errors vary substantially depending on the sector or product considered. For the details of the average, standard deviation, and range of footprint captured for specific sector can be found in [8].

The rapid growth of China's urbanization has been realized at an excessively high cost of energy and carbon emission, and this will not be sustainable in the long run. As one of the four municipalities directly under the Central Government, the low-carbon economic construction of Chongqing city plays an important role in responding to climate change and makes new contributions to protecting the global climate. Based on the detailed analyses presented in this study, it can be concluded that a conservation culture can be established in the following manner:

5.1. Promoting the transformation of industrial structure

To accelerate the transformation of economic development, the city needs to upgrade the industrial structure. Accordingly, a transition should occur from secondary industry serving as the major driving force to primary, secondary and tertiary industries jointly driving economic growth. Also, a transition is needed from the current heavy reliance on energy and material resource consumption to relying on advances in science and technology and management innovation.

More efforts are needed to establish an exit mechanism for backward production capacity and eliminate or reduce production from inefficient and carbon-intensive industrial processes, technologies and facilities, such as the nonmetal minerals mining and dressing sector (sector 5) and the petroleum, coking and nuclear fuel processing sector (sector 11). Alternately, high technology and service industries that have low carbon emission intensities should be encouraged like the paper-making, printing and cultural, educational and sports goods sector (sector 10), communication equipment, computers and other electronic equipment sector (sector 19) and Gas Production and Supply of Chongqing sector (sector 23). Overall, it is favorable to shift the industrial structure from heavy sectors to industries that produce value-added products as well as service industries.

The Municipal Development and Reform Commission (MDRC) of Chongqing is responsible for making regulations and policies to reduce carbon emission and speed up the formation of systems and mechanisms for sustainable development, including closure of small and inefficient industrial facilities. Nowadays, existing MDRC carbon control measures generally focus on sectoral direct emissions (Tier 1) and emissions from direct purchases of energy (Tier 2), but much less on indirect emissions upstream and downstream of the supply chain (optional Tier 3). According to our results, a large proration of a sector's carbon footprint is attributed to Tier 3 sources. Thus, the knowledge of Tier 3 footprints can be used in setting sectoral reduction goals to pursue emissions mitigation not just within their own plants but also across their supply chain. Also, the results of the sectoral contribution to the whole city can be used for urban financial instruments like

incentives of tax and finance, preferential tax policies and energy price adjustments for sectoral allocation.

5.2. Optimizing the energy structure and improving the proportion of clean energy

The power structure should be optimized by giving priority to clean energy. The electricity, steam production and supply sector is one of the main sources of direct carbon emissions in Chongqing. Currently, this sector primarily uses thermal power to generate electricity, while biogas, water, solar, wind and other renewable energy sources, and nuclear energy account for a small proportion. Chongqing is fed by the Yangtze, Wu Jialing and Fu rivers and their branches constituting 124 waterbodies with more than 10 Kilowatts hydropower resources. The solar energy resources of Chongqing are similar to those of the Sichuan Basin. The annual sunshine duration is between 1100 and 1600 h, and the annual global radiation is about 3400–4180 MJ/m^2. Finally, the wind energy resources amount to 23.595 million Kilowatts. In fact, the exploitable wind resource with a working platform height of 10 m and wind power density of 150 W/m^2 can exceed 2 million Kilowatts [65]. However, compared to the other provinces and cities of western China, wind energy resources of Chongqing are not as rich. Overall, natural gas utilization should be developed vigorously, and hydropower stations should be constructed in a sustainable manner. The hybrid utilization of solar, wind, geothermal and biomass energy should also be encouraged and supported.

Acknowledgement

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References

[1] Xu X, Huo H, Liu J, Shan Y, Li Y, Zheng H, et al. Patterns of CO_2 emissions in 18 central Chinese cities from 2000 to 2014. J Clean Prod 2018;172:529–40.
[2] Gu C, Yuan X. Urban greenhouse gas inventory and methods in China. Urban Environ Urban Ecol 2011;24:1–4.
[3] Cai B, Zhang L. Urban CO_2 emissions in China: spatial boundary and performance comparison. Energ Policy 2014;66:557–67.
[4] Satterthwaite D. Cities' contribution to global warming: notes on the allocation of greenhouse gas emissions. Environ Urban 2008;20:539–49.
[5] Wiedmann T, Minx JA. A definition of carbon footprint; 2007 < http://www.censa.org.uk/docs/ISA-UK_Report_07-01_carbon_footprint.pdf > [accessed 13.05.16].
[6] Hu Y, Lin J, Cui S, Khanna NZ. Measuring urban carbon footprint from carbon flows in the global supply chain. Environ Sci Technol 2016;50(12):6154–63.
[7] Huang YA, Lenzen M, Weber CL, Murray J, Matthews HS. The role of input-output analysis for the screening of corporate carbon footprints. Econ Syst Res 2009;21:217–42.
[8] Huang YA, Weber CL, Matthews HS. Categorization of scope 3 emissions for streamlined enterprise carbon footprinting. Environ Sci Technol 2009;43:8509–15.
[9] Chen J, Chen J. Supply chain carbon footprinting and responsibility allocation under emission regulations. J Environ Manag 2017;188:255–67.
[10] Liu Z, Feng K, Hubacek K, Liang S, Anadon LD, Zhang C, et al. Four system boundaries for carbon accounts. Ecol Model 2015;318:118–25.
[11] Larsen HN, Hertwich EG. Identifying important characteristics of municipal carbon footprints. Ecol Econ 2010;70(1):60–6.
[12] World Resources Institute. The greenhouse gas protocol: a corporate accounting and reporting standard; 2004 < http://www.ghgprotocol.org/files/ghgp/public/ghg-protocol-revised.pdf > [accessed 13.02.16].
[13] World Resources Institute. Greenhouse gas protocol initiative: new guidelines for product and supply chain accounting and reporting. World Business Council for Sustainable Development; 2009.
[14] ICLEI-Local Governments for Sustainability. Local government operation protocol: for the quantification and reporting of greenhouse gas emissions inventories; 2008 < http://www.arb.ca.gov/cc/protocols/localgov/pubs/lgo_Protocol_v1_1_2010-05-03.pdf > [accessed 13.02.16].
[15] IPCC. IPCC guidelines for national greenhouse gas inventories; 2006 < http://www.ipcc.ch/ipccreports/methodology-reports.htm > [accessed 13.02.16].
[16] Wiedmann TO, Chen G, Barrett J. The concept of city carbon maps: a case study of Melbourne, Australia. J Ind Ecol 2016;20(4):676–91.
[17] Liu Z. National carbon emissions from the industry process: Production of glass, soda ash, ammonia, calcium carbide and alumina. Appl Energy 2016;166:239–44.
[18] Lin J, Hu Y, Cui S, Kang J, Ramaswami A. Tracking urban carbon footprints from production and consumption perspectives. Environ Res Lett 2015;10:054001.
[19] Tan XC, Dong LL, Chen DX, Gu BH, Zeng Y. China's regional CO_2 emissions reduction potential: a study of Chongqing city. Appl Energy 2016;162:1345–54.
[20] Liu Z, Liang S, Geng Y, Xue B, Xi F, Pan Y, et al. Features, trajectories and driving forces for energy-related GHG emissions from Chinese mega cites: the case of Beijing, Tianjin, Shanghai and Chongqing. Energy 2012;37(1):245–54.
[21] Larsen HN, Hertwich EG. Implementing carbon-footprint-based calculation tools in municipal greenhouse gas inventories. J Ind Ecol 2010;14(6):965–77.
[22] Hillman T, Ramaswami A. Greenhouse gas emission footprints and energy use benchmarks for eight U.S. cities. Environ Sci Technol 2010;44(6):1902–10.
[23] Yang J, Chen B. Global warming impact assessment of a crop residue gasification project—a dynamic LCA perspective. Appl Energy 2014;122:269–79.
[24] Onat NC, Kucukvar M, Tatari O. Scope-based carbon footprint analysis of US residential and commercial buildings: an input-output hybrid life cycle assessment approach. Build Environ 2014;72:53–62.
[25] Tan X, Mu Z, Wang S, Zhuang H, Cheng L, Wang Y, et al. Study on whole-life cycle automotive manufacturing industry CO_2 emission accounting method and application in Chongqing. Proc Environ Sci 2011;5:167–72.
[26] Lenzen M. Differential convergence of life-cycle inventories toward upstream production layers. J Ind Ecol 2002;6(3–4):137–60.
[27] Meng FX, Liu GY, Yang Z, Hao Y, Zhang Y, Ulgiati S. Life cycle perspective for urban energy use and carbon emissions: a case study of Xiamen, China. J Environ Account Manage 2017;5(1):71–6.
[28] Suh S, Huppes G. Methods for life cycle inventory of a product. J Clean Prod 2005;13:687–97.
[29] Peters GP, Hertwich EG. A comment on "Functions, commodities and environmental impacts in an ecological-economic model". Ecol Econ 2006;59(1):1–6.
[30] Leontief WW. Input-output economics. 2nd ed. New York: Oxford University Press; 1986.
[31] Joshi S. Product environmental life-cycle assessment using input-output techniques. J Ind Ecol 1999;3:95–120.
[32] Li JS, Xia XH, Chen GQ. Optimal embodied energy abatement strategy for Beijing economy: based on a three-scale input-output analysis. Renew Sustain Energy Rev 2016;53:1602–10.
[33] Chen B, Yang Q, Li JS, Chen GQ. Decoupling analysis on energy consumption, embodied GHG emissions and economic growth—the case study of Macao. Renew Sustain Energy Rev 2017;67:662–72.
[34] Chen B, Li JS, Wu X, Han M, Zeng L, Li Z, et al. Global energy flows embodied in international trade: a combination of environmentally extended input-output analysis and complex network analysis. Appl Energy 2018;210:98–107.
[35] Wang SG, Chen B. Energy-water nexus of urban agglomeration based on multi-regional input-output tables and ecological network analysis: a case study of the Beijing-Tianjin-Hebei region. Appl Energy 2016;178:773–83.
[36] Wang SG, Cao T, Chen B. Urban energy-water nexus based on modified input-output analysis. Appl Energy 2017;196:208–17.
[37] Wang SG, Liu Y, Chen B. Multiregional input-output and ecological network analyses for regional energy-water nexus within China. Appl Energy 2017. https://doi.org/10.1016/ j.apenergy.2017.11.093.
[38] Chen B, Han MY, Peng K, Zhou SL, Shao L, Wu XF, et al. Global land-water nexus: agricultural land and freshwater use embodied in worldwide supply chains. Sci Total Environ 2017;613:931–43.
[39] Chen B, Yang Q, Zhou S, Li JS, Chen GQ. Urban economy's carbon flow through external trade: spatial-temporal evolution for Macao. Energy Policy 2017;110:69–78.
[40] Brizga J, Feng K, Hubacek K. Household carbon footprints in the Baltic States: a global multi-regional input–output analysis from 1995 to 2011. Appl Energy 2017;189:780–878.
[41] Su B, Ang BW. Multiplicative decomposition of aggregate carbon intensity change using input–output analysis. Appl Energy 2015;154:13–20.
[42] Miller RE, Blair PD. Input-output analysis: foundations and extensions. 2nd ed. New York: Cambridge University Press; 2009.
[43] Igos E, Rugani B, Rege S, Benetto E, Drouet L, Zachary DS. Combination of equilibrium models and hybrid life cycle-input-output, analysis to predict the environmental impacts of energy policy scenarios. Appl Energy 2015;145:234–45.
[44] Gibon T, Wood R, Arvesen A, Bergesen JD, Suh S, Hertwich EG. A methodology for integrated, multiregional life cycle assessment scenarios under large-scale technological change. Environ Sci Technol 2015;49:11218–26. https://doi.org/10.1021/acs.est.5b01558.
[45] Hendrickson CT, Lave LB, Matthews HS. Environmental life cycle assessment of goods and services: an input-output approach. Routledge; 2010.
[46] Ramaswami A, Tong K, Fang A, Lal R, Nagpure S, Li Y, Yu H, Jiang D, Russell A, Shi L, Chertow M, Wang Y, Wang S. Urban cross-sector actions for carbon mitigation with local health co-benefits in China. Nat Climate Change 2017;7(10). https://doi.org/10.1038/nclimate3373.
[47] Yang J, Chen B. Carbon footprint estimation of Chinese economic sectors based on a three-tier model. Renew Sust Energy Rev 2014;29:499–507.
[48] Peters GP, Hertwich EG. Structural analysis of international trade: environmental impacts of Norway. Econ Syst Res 2006;18(2):155–81.
[49] Yang Y, Ingwersen WW, Meyer DE. Exploring the relevance of spatial scale to life cycle inventory results using environmentally-extended input-output models of the United States. Environ Model Softw 2018;99:52–7.
[50] Potting J, Hauschild M. Spatial differentiation in life cycle impact assessment: a

decade of method development to increase the environmental realism of LCIA. Int J Life Cycle Assess 2006;11:11–3.
[51] Davis SJ, Peters GP, Caldeira K. The supply chain of CO_2 emissions. Proc Natl Acad Sci 2011;108(45):18554–9.
[52] Munksgaard J, Pedersen KA. CO_2 accounts for open economies: producer or consumer responsibility? Energy Policy 2001;29:327–34.
[53] Dhakal S. Urban energy use and carbon emissions from cities in China and policy implications. Energy Policy 2009;37:4208–19.
[54] Bi J, Zhang R, Wang H, Liu M, Wu Y. The benchmarks of carbon emissions and policy implications for China's cities: case of Nanjing. Energy Policy 2011;39(9):4785–94.
[55] Lin J, Liu Y, Meng F, Cui S, Xu L. Using hybrid method to evaluate carbon footprint of Xiamen City, China. Energy Policy 2013;58(5):220–7.
[56] Matthews HS, Hendrickson CT, Weber CL. The importance of carbon footprint estimation boundaries. Environ Sci Technol 2008;42:5839–42.
[57] Chongqing Statistical Year book 1998–2015.
[58] Alcántara V, Padilla E. Input-output subsystems and pollution: an application to the service sector and CO_2 emissions in Spain. Ecol Econ 2009;68(3):905–14.
[59] Minx JC, Baiocchi G, Peters GP, Weber CL, Guan DB, Hubacek KA. Carbonizing Dragon: China's fast growing CO_2 emissions revisited. Environ Sci Technol 2011;45:9144–53.
[60] Hertwich EG, Peters GP. Carbon footprint of nations: a global, trade-linked analysis. Environ Sci Technol 2009;43:6414–20.
[61] Menzies GF, Turan S, Banfill PFG. Life-cycle assessment and embodied energy: a review. Proc Inst Civil Eng Constr Mater 2007;160(4):135–44.
[62] Lindner S, Guan D. A hybrid-unit energy input-output model to evaluate embodied energy and life cycle emissions for China's economy. J Ind Ecol 2014;18(2):201–11.
[63] National Bureau of Statistics of China. 2007 input-output tables in China. Beijing: China Statistics Press; 2008. [in Chinese].
[64] Chinese Academy for Environment Planning. Analysis and forecast of environment and economic about the key industries of energy saving and emission reduction in China from 2009–2020. Beijing: China Environmental Science Press; 2009. [in Chinese].
[65] CDRC. Chongqing development and reform commission. compilation of “Twelveth Five-Year” plan of Chongqing previous research achievements; 2010 [in Chinese].